

Dual-task Interference When a Response is Not Required

Mark Van Selst (MVSELST@VISION.ARC.NASA.GOV)

James C. Johnston (JCJOHNSTON@MAIL.ARC.NASA.GOV)

NASA Ames Research Center, MS 262-2, Moffett Field, CA, 94035-1000

Abstract

When subjects are required to respond to two stimuli presented in rapid succession, responses to the second stimulus are delayed. Such dual-task interference has been attributed to a fundamental processing bottleneck preventing simultaneous processing on both tasks. Two experiments show dual-task interference even when the first task does not require a response. The observed interference is caused by a bottleneck in central cognitive processing, rather than in response initiation or execution.

Introduction

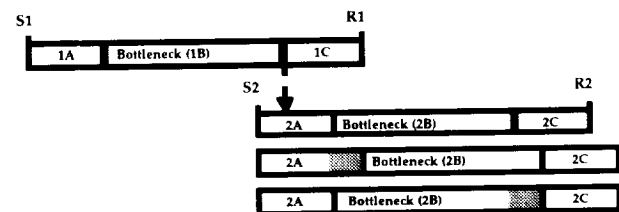
When human observers are required to respond to two stimuli presented in rapid succession, responses to the second stimulus are typically delayed, often by several hundred milliseconds. This form of dual-task interference, known as the psychological refractory period (PRP) effect, has been found with a wide range of tasks, including very simple ones. Because the phenomena appears to reflect a severe limitation on human parallel task performance, it has been the subject of intensive empirical and theoretical interest.

A considerable body of empirical evidence indicates that the PRP effect is caused by a processing bottleneck that prevents one or more stages of processing from being carried out simultaneously on both tasks (Pashler, 1994; Pashler & Johnston, 1989). Thus, one or more stages of task 2 processing are subject to *postponement*, and cannot take place until after the corresponding stage(s) of task 1 are completed. Although it is commonly hypothesized that the bottleneck is a central processing limitation (Welford, 1959; Smith, 1969; Pashler, 1994), the bottleneck locus remains controversial. In this paper we examine the extent to which PRP interference depends upon the mental processing required to set up and execute responses. Evidence from the current investigation should help to pin down whether any output processing is required for PRP interference to obtain.

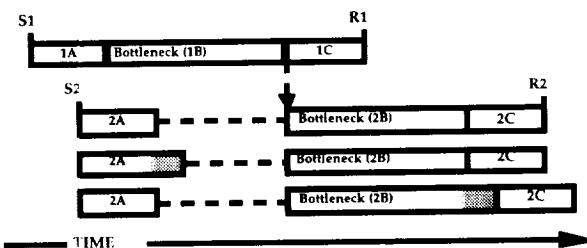
The timeline for a simple bottleneck model is illustrated in Figure 1. For simplicity, we assume that each task can be decomposed into three stages — A, B, and C. Task 1 processing begins with the presentation of the task 1 stimulus, S1, and continues through the three stages, ultimately producing the overt response R1. If the stimuli are widely separated in time (top panel, long stimulus onset asynchrony [SOA]), processing on task 2 is unimpeded, yielding a baseline for task 2 response times (RT2). If, however, the SOA is very short (bottom panel), task 2 is subject to interference. Early perceptual processing on task 2

(stage 2A) starts with the onset of S2, but task 2 processing is held up at the start of 2B and cannot resume until the bottleneck stage (stage B) is cleared by task 1. According to this model, the increase in RT2 (the PRP) is caused by the forced postponement of task 2 processing. This postponement — the gap in the timeline for task 2 processing between 2A and 2B — is known as *cognitive slack*.

Long SOA



Short SOA



$$RT1 = 1A + 1B + 1C$$

$$RT2 = \max(1A + 1B + \text{switch}, SOA + 2A) + 2B + 2C - SOA$$

Figure 1. Task 2 processing (2A, 2B, 2C) is unaffected by Task 1 processing (1A, 1B, 1C) when the stimuli for the two tasks (S1 and S2) are far apart in time (Long SOA, upper panel). Task 2 processing at stage 2B has to wait for Task 1 processing at stage 1B to run to completion before Task 2 processing can continue. When the Task 2 stimulus is presented in close temporal proximity to the Task 1 stimulus (Short SOA, lower panel), Task 2 processing may be delayed (the postponement is shown by the horizontal dashed lines). This delay in Task 2 processing leads to longer response time to Task 2 (RT2: the time interval between S2 and R2) with decreasing SOA. Additionally, the effect of pre-bottleneck task 2 manipulations (shaded 2A) have less of an effect on RT2 with decreasing SOA since the effect gets absorbed into the "slack time" while waiting for the completion of Task 1 processing at stage 1B (middle Task 2 diagrams). The impact of Post-bottleneck task 2 manipulations (shaded 2B) are unaffected by SOA.

Figure 1 also illustrates a unique prediction of postponement models. Manipulations affecting pre-bottleneck processing (shown by the added shaded region of 2A) impact RT2 only at the long SOA, when the bottleneck does not limit performance. At the short SOA adding time to 2A has no effect on RT2 because the added time is *absorbed into cognitive slack* while task 2 is waiting for the bottleneck stage (Pashler & Johnston, 1989; Schweickert & Boggs, 1984).

Suppose, however, a manipulation increases the duration of the central stage of task 2 (shown by the added shaded region of 2B). Stage 2B occurs after the cognitive slack in task 2 processing, thus absorption into slack cannot occur and the added time increases RT2 at the long and short SOAs.

Empirical tests of these predictions have supported central bottleneck models. Manipulations of stage 2A, such as stimulus degradation, have attenuated effects at short SOAs (Pashler & Johnston, 1989; De Jong, 1993). Manipulation of central stages, such as response selection, are reportedly unaffected by SOA (e.g., stimulus-response compatibility, McCann & Johnston, 1992; number of response alternatives, Van Selst and Jolicoeur, 1997). For a review, see Pashler (1994).

In this paper, we examine the role of response processes in PRP interference by varying the response requirements of task 1. Some task 1 stimuli require a response (Go trials). For these trials, task 1 will require all the usual processing stages, including central response selection and response initiation. Other task 1 stimuli will not require a response (No-Go trials). These no-go trials clearly do not require response initiation and may or may not require response selection. At most, no-go processing should only require the minimal decision to not respond.

If RT2 is slowed with decreasing SOA for the no-go trials (no-go PRP), the bottleneck limiting performance is not a response initiation or response execution bottleneck.

If RT2 is slowed for both go and no-go trials, but more for go trials than for no-go trials, the difference in the PRP obtained should reflect the difference in the amount of bottleneck processing. We argue that any obtained difference primarily reflects "extra" or "additional" central processing.

The present experiments also allow us to test one of the claims of Meyer, Kieras, Lauber, Schumacher, Glass, Zurbriggen, Gmeindl, and Apfelblat (1995). Meyer et al. claim that the central bottleneck is not a necessary structural property of human cognitive architecture, but reflects a strategic choice of subjects to produce overt responses in sequential order. On no-go trials, there is no overt R1 response to which R2 needs to be sequenced, so there is no strategic reason for delaying R2. Hence, if PRP delays are strategic, they should disappear on no-go trials.

Previous work has indicated that task 1 no-go trials do produce dual-task interference (e.g., Bertelson and Tisseyre, 1969; De Jong, 1993; Kerr, 1983; Smith, 1967). Although this interference is consistent with the central bottleneck model, there are alternate hypotheses.

Most previous dual-task experiments using the go/no-go

procedure have had only a single possible go response. Under these conditions, subjects may begin the antecedents of responding on *all* trials (analogous to a batter preparing to swing on all pitches) and upon identifying the no-go stimulus, may have to initiate processes to halt the response in progress (like the batter who "checks" his swing on bad pitches). Thus, with only a single type of go response, no-go PRP may reflect output processing after all.

To avoid this problem, Bertelson and Tisseyre (1969) used two different go stimuli, each requiring a different response. With this design, the required response is not known until after central processing; thus there should be no pre-initiation of output processing on no-go trials.

Bertelson and Tisseyre report the surprising result that task 1 no-go trials not only produce PRP interference, but that the interference is just as much as for go trials. This finding may reflect the use of complicated stimulus-response mappings and the potential for cross-talk between the responses from the two tasks (each task required manual responses, and each used fingers from both hands). We wish to investigate the much simpler situation where only highly compatible stimulus-response mappings are required, and each task uses a different response modality. This should facilitate decoupling output processing for the two tasks (McLeod, 1977). Hence we retain Bertelson and Tisseyre's use of multiple alternative go stimuli, but are careful to avoid unnecessary interference in early and late peripheral processing. In our design, one task has visual stimuli and the other auditory, and the responses are made by hand and foot (Experiment 1), or by voice and hand (Experiment 2).

Experiment 1

One of our goals was to carry out tests of the bottleneck model of PRP interference on the same data set that tested the differential effects of go and no-go processing on the size of the PRP.

We used two tests of the central bottleneck model. To test for absorption into slack (see above) we manipulated the difficulty of task 2 stimulus processing. As task 2, subjects judged whether a letter was an "A" or an "H". Letters were either normal or distorted. In earlier PRP experiments this manipulation was absorbed into slack (Johnston, McCann, & Remington, 1995). Our interest is to see if this absorption will occur on no-go trials despite their postulated minimal processing requirements (i.e., the "decision" not to respond).

Task 1 required subjects to judge the pitch change between an initial reference tone and a probe tone (S1). Four levels of pitch change occurred. Two levels of pitch increase constituted go signals, each requiring a different response. Two levels of pitch decrease constituted no-go signals, to which no response was required.

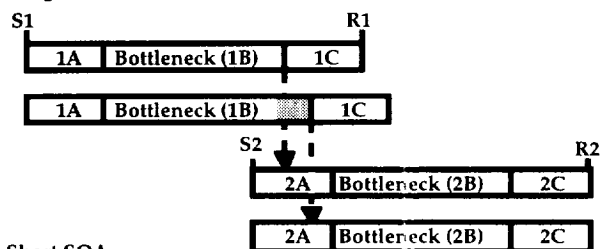
Because smaller pitch changes are harder to discriminate than larger pitch change, the task 1 stimulus judgments were either 'easy' or 'hard'. This allowed us to test another prediction of the central bottleneck model — the carry-forward of task 1 difficulty onto RT2 at short SOAs (where postponement occurs).

The top panel of Figure 2 shows that at long SOAs, where the bottleneck does not restrict task 2 processing, task 1 difficulty does not affect RT2. At short SOAs, where the bottleneck limits performance, increases in the duration of either stage 1A or 1B will further delay release of the bottleneck, thus increasing both RT1 and RT2 (Smith, 1967). If the central bottleneck model is valid, we anticipate task 1 difficulty to carry-forward onto RT2 for both go and no-go trials.

Method

Subjects. Subjects were 20 undergraduates (10 male) aged 18 to 33 (Median = 21) tested at the NASA Ames Research Center for pay or psychology course credit. An additional 9 subjects were eliminated due to excessively high error rates (>25% of the trials had an error on task 1 and/or task 2).

Long SOA



Short SOA

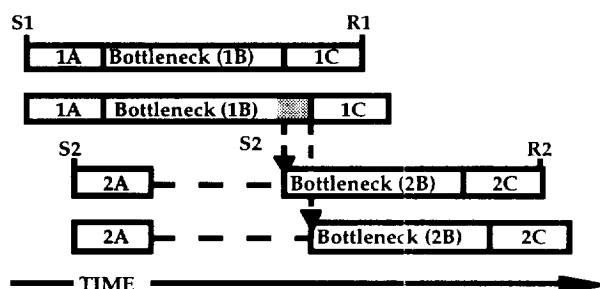


Figure 2. At the short SOA, but not the long SOA, Task 1 difficulty carries-over onto RT2. At the long SOA (top panel), lengthening Task 1 bottleneck processing (shaded 1B) does not affect Task 2 response times because Task 2 processing is independent of Task 1 processing. At the short SOA (bottom panel), lengthening Task 1 bottleneck processing (shaded 1B) lengthens RT2 because Task 2 processing at stage 2B is held up while waiting for bottleneck processing for Task 1 at stage 1B to be completed.

Stimuli and Apparatus. The tone sequence consisted of a 150 ms 800 Hz reference tone, a 100 ms silent interval, then a 150 ms presentation of the S1 tone. The S1 frequency on go trials was either 5000 or 2000 Hz. The S1 frequency on no-go trials was 320 or 128 Hz.

The S2 was a white "A" or "H" presented at fixation against a dark background. All S2 stimuli were vertically symmetrical shapes composed of three line-segments. The

viewing distance was 61 cm. The letters all fit within a $1.41^\circ \times 1.21^\circ$ visual angle bounding box (not presented). To distort the letters the outer line segments were tilted and the horizontal segment lowered (Johnston, McCann, & Remington, 1995). S2 was shown for 500 ms.

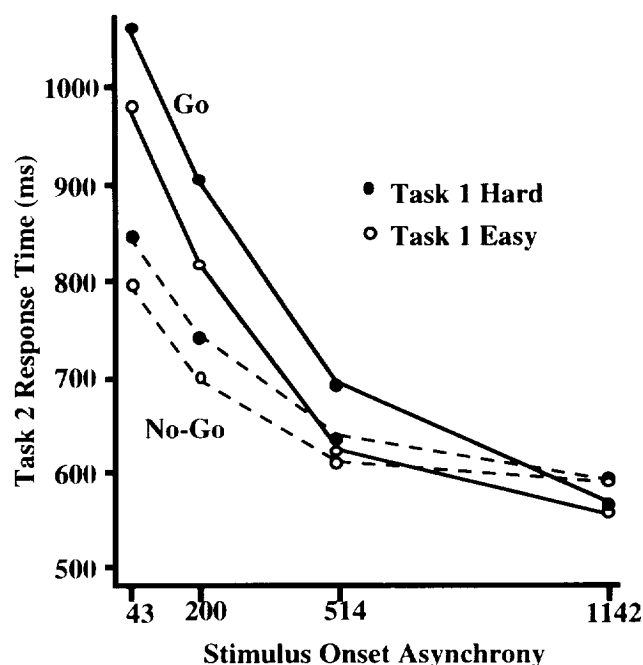


Figure 3. Hard vs. Easy RT2. Consistent with the predictions shown in Figure 2, the Task 2 response times (RT2) reflect the difficulty of the Task 1 judgments at the shortest SOAs but do not do so at the longest SOA. This effect is as pronounced for no-go trials as for go trials.

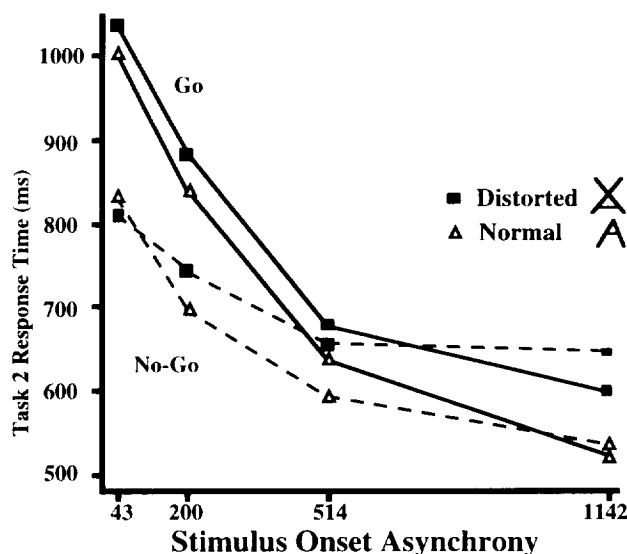


Figure 4. Distorted vs. Normal RT2. Consistent with the predictions shown in Figure 1, the Task 2 response times (RT2) decreasingly reflect the processing costs of the distorted Task 2 stimuli with decreasing SOA. This is true for both go and no-go trials.

Procedure. Instructions stressed the importance of speed and accuracy on both tasks. Each trial began with the presentation of a fixation cross for 250 ms, a pause of 250 ms, and then the tone sequence. The SOA between S1 and S2 was 43, 200, 514, or 1142 ms. Responses less than 100 ms or greater than 2000 ms were considered errors. The trial ended with a 1000 ms concurrent presentation of accuracies, and, if correct, response times. The inter-trial interval was 750 ms.

The task 1 go trial response mappings used the right index finger (the 5 key on the numeric keypad) for the very high (5000 Hz) tones and the right middle finger (the 2 key) for the medium high (2000 Hz) tones. Task 2 responses used a left foot-press for "A" and a right foot-press for "H".

The experimental session consisted of two blocks of 64 practice trials and five blocks of 64 experimental trials. Each block consisted of a random ordering of one complete factorial cross of the go/no-go x task 1 difficulty x SOA x A/H x normal/distorted design.

Results

Correct RTs and error rates for each task were subjected to separate within-subject ANOVAs. Each correct RT cell for each task for each subject underwent independent RT outlier elimination (Van Selst and Jolicoeur, 1994a, 1997). Outlier elimination excluded 0.9% of these trials as RT1 outliers and 2.6% of the remaining trials as RT2 outliers.

As expected, RT1 (not shown) was relatively flat across SOAs. The principal RT1 (go trial) effect is a 125 ms main effect of task 1 difficulty, $F(1,19)=57.2$, $p<.001$. The error rate analyses produced results consistent with the response time results. The overall error rate was 5.8% on task 1 and 6.1% on task 2.

The RT2 results in Figure 3 are broken down by whether task 1 was an easy or hard tone judgment. The PRP effect ($RT_{2\text{-short}} - RT_{2\text{-long}}$) was larger for go trials (461 ms) than for no-go trials (232 ms), producing a strong SOA by go/no-go interaction, $F(3,57)=89.4$, $p<.001$. The task 1 difficulty effect carried forward onto RT2 at short SOAs but not at long SOAs, producing an interaction for RT2 between task 1 difficulty and SOA, $F(3,59)=7.14$, $p<.001$ (Fig. 3). Note that this carry-over effect occurred on both no-go and go trials.

Figure 4 shows the same data broken down by whether S2 was normal or distorted. The overall effect of normal/distorted on RT2 was significant, $F(1,19)=24.9$, $p<.001$. But, more importantly, the effect decreased substantially with decreasing SOA, $F(3,57)=15.9$, $p<.001$.

Discussion

There are four major findings: 1) no-go trials produce PRP interference. 2) no-go trials produce less PRP interference than go trials. 3) Task 1 difficulty carried over onto RT2 at short SOAs but not at long SOAs. 4) The effect of distorting S2 was substantial at long SOAs but virtually disappeared at short SOAs. We will discuss each of these findings in turn.

1) *Substantial PRP interference was found on no-go trials.* This indicates that the PRP can occur with minimal involvement of task 1 response processes. This finding is particularly important because the no-go PRP cannot readily be attributed to "stop" processing (as may have been the case with the experiments of De Jong and Kerr) or to response requirements likely to induce S-R mapping difficulties (as may have been the case with Bertelson and Tisseyre's experiment). The contentious issue of whether this result means that the PRP can occur with no response processing at all on task 1 will be discussed later.

2) *Go trials produced substantially more PRP than no-go trials.* Our results clearly indicate that additional response processing on go trials prolong the bottleneck. This result is consistent with the results of De Jong (1993). The near-equivalent PRP effects for go and no-go trials reported by Bertelson and Tisseyre (1969) and by Kerr (1983) must have been obtained because of the peculiarities of the difficult stimulus-response mappings used.

The natural interpretation of the lesser PRP for no-go trials than for go trials is that the central bottleneck is cleared by no-go trials faster than for go trials. Alternatively, it remains possible that the process of switching mental resources from task 1 to task 2 is harder after go trials.

3) The finding that *task 1 difficulty carries-forward onto task 2 processing at the short but not the long SOAs* provides support for the bottleneck model. The fact that this "carry-over effect" occurred for no-go as well as go trials confirms that the central bottleneck model holds even for the no-go PRP. Hence there is further support for the notion that eliminating or drastically reducing response processing on task 1 shortens the central bottleneck, but does not qualitatively change the nature of the interference.

4) This conclusion is further strengthened by the finding that *the overall effect of distorting S2 on RT2 is virtually completely absorbed into slack at short SOAs*, for both go trials and no-go trials.

Experiment 2

From Experiment 1, we know that the bottleneck occurs even with minimal response processing on task 1 (no-go trials). In Experiment 2 we asked whether these conclusions could be extended to a condition with even greater separation of response modalities. Thus, in Experiment 2 we extend our design to encompass a condition of extremely low similarity of the cross-task S-R mappings. A voice response was used for task 1, a manual response for task 2. The change from manual-foot to vocal-manual permits us to examine dual-task interference while further minimizing the likelihood of cross-talk at response output

Method

Subjects. Subjects were 24 undergraduates (13 male) aged 16 to 37 (Median = 20). Two additional subjects produced excessively high error rates (>20% errors overall), resulting in the exclusion of their data.

this conclusion with our other result — the much greater PRP on go trials than no-go trials — it is clear that response selection is part of the bottleneck.

In comparing go and no-go processing, it is evident that go trials, in addition to actually requiring response initiation and execution, would also require more response selection operations (since the mental code for a to-be-made response must be established). It may be that this difference at response selection is responsible for the difference in the magnitude of go and no-go PRP (i.e., go/no-go thought of as a manipulation of when task 1 clears the bottleneck). This interpretation of our results is consistent with a central bottleneck model.

If the bottleneck consists of the more central (and abstract) stages of both stimulus processing and the more central (and abstract) stages of response selection, then we arrive at the hypothesis that the cause of the bottleneck is that humans have something like a central processor which can only work on one task at a time. It seems unlikely given our knowledge of multiple processing regions in the brain that the same hardware is used for all "central" processing. Nevertheless it remains plausible that the control structure used does not permit the various central processors to work on different tasks at the same time.

While speculative, the conclusion that several different mental processes are involved in the central bottleneck provides an answer to another question, which is why PRP interference is so widespread. If it involves a number of different mental processes, then it is not surprising that there are so few known cases in which PRP interference is absent (Greenwald, 1972; Johnston & Delgado, 1993; McLeod & Posner, 1984).

Acknowledgments

This project was funded by NASA and the National Research Council. Roger Remington, Eric Ruthruff, and Robert McCann provided useful discussion. Katie McCutchen, Shelly Whitsell, and Jeannine Couse ran the subjects for these experiments.

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Stimuli. The reference tone was changed to 500 Hz. S1 was either 80, 200, 1250, or 3125 Hz. The viewing distance was reduced to 41 cm.

Procedure. For half of the subjects the higher tones were the two go stimuli. For the remaining subjects, the lower tones were the two go stimuli. task 1 required a verbal response on the go trials. For the lower of the two go tones, the subject was to say "five". For the higher of the two go tones, the subject was to say "ten". To make the letter response, the subject was to press the 1 or 2 key on the numeric keypad (A:1, H:2).

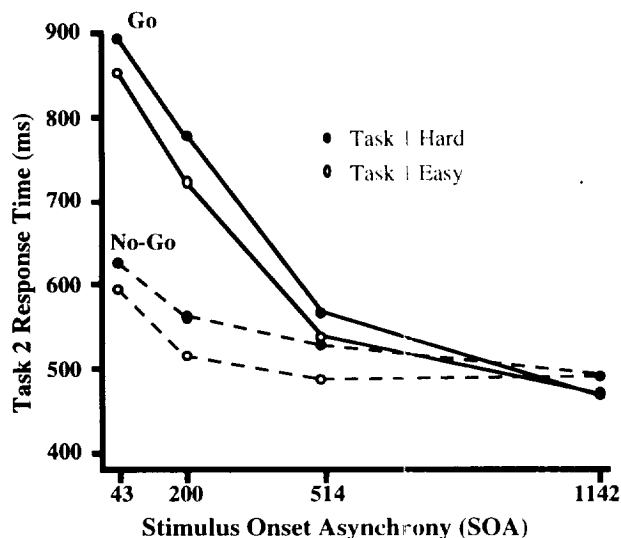


Figure 5. Hard vs. Easy RT2 (Exp. 2). Task 1 difficulty carries-over onto RT2 at the short, but not the long, SOAs. This result is found for both go and no-go trials.

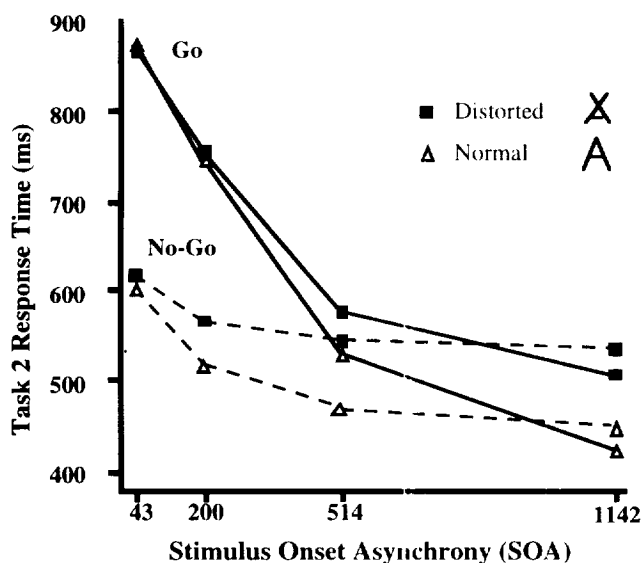


Figure 6. Normal vs. Distorted RT2 (Exp. 2). The processing costs associated with distorting the Task 2 have less of an impact on Task 2 response times with decreasing SOA. This result is found for both go and no-go trials.

Results

As is shown in Figures 5 and 6, the main results of Experiment 1 were closely replicated. The PRP for go trials (396 ms) was larger than that for no-go trials (104 ms), $F(3,69)=87.6$, $p<.001$. Task 1 difficulty carried over onto RT2 at the shorter SOAs, $F(3,69)=7.08$, $p<.001$; and the distorted-normal RT2 difference decreased with decreasing SOA, $F(3,69)=16.6$, $p<.001$.

Discussion

Despite the switch from a manual-foot response pairing to a vocal-manual response pairing, no-go trials still produce a robust PRP effect. Furthermore, both the absorption of the effect of letter distortion and the carry-over of task 1 difficulty confirm the predictions of the central bottleneck model for both go and no-go processing. As before, the larger go trial PRP than no-go trial PRP is interpreted to indicate that go trial processing occupies the bottleneck for a longer period of time than no-go trial processing.

The increase in the magnitude of the PRP effect for go and no-go trials relative to Experiment 1 could reflect any of a number of task differences including the stimuli and/or the response requirements. The fact that qualitatively similar effects occurred with different pairs of response modalities supports the generality of the central bottleneck model of PRP interference.

General Discussion

The predictions of the central bottleneck model were strongly confirmed. The most critical finding — that no-go trials produce a substantial PRP effect — indicates that late response processes, including the establishment of a positive mental code for a to-be-made response, are not necessary to produce dual-task interference.

It is possible that no-go trials do not require response selection, and that the bottleneck occurs during high-level stimulus classification, as argued by Johnston & McCann (in preparation). The empirical basis for their argument is that analog stimulus classification (box-width judgment in their case) is not absorbed into slack, and hence appears to be part of the bottleneck. Also consistent is that the effect of letter disorientation on mirror/normal judgments is largely unaffected by SOA (Ruthruff & Miller 1994, Van Selst & Jolicoeur, 1994b).

On the other hand, deciding not to respond may constitute an act of response selection. Although much simpler than setting up a mental code for a to-be-made response, this residual act of response selection might still be the locus of the central bottleneck. Thus it remains possible that the response selection stage is the first (and presumably only) stage responsible for no-go interference.

Suppose, however, that we provisionally accept that the no-go PRP is produced by a limitation at stimulus classification — that no-go trials do not involve response selection (no responses are made, after all). If we juxtapose

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